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Low density polyethylene, expanded polystyrene and expanded polypropylene: Strain rate and size effects on mechanical properties

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ABSTRACT

Polymeric foam materials may be used as energy absorbing materials for protection in impact scenarios, and design with these materials requires the mechanical properties of foams across a range of deformation rates, where high deformation rate testing often requires small samples for testing. Owing to their cellular macrostructure, and the large deformations that occur during loading of foams, the measured stress-strain response of a foam material may be influenced by the sample size. In this study, the mechanical properties of three closed-cell polymeric foams (Low Density Polyethylene, Expanded Polystyrene and Expanded Polypropylene) at two different densities were investigated over a range of deformation rates from 0.01 s^{-1} to 100 s^{-1}. For each foam material, three different nominal sample sizes (10 mm, 17 mm and 35 mm) were tested. On average, the polymeric foam materials exhibited increasing stress with increasing deformation rate, for a given amount of strain.

Density variation was identified at the sample level, with smaller samples often exhibiting lower density. Expanded Polystyrene demonstrated the highest variability in sample density and corresponding variability in mechanical response, qualitatively supported by observed variations in the macrostructure of the foam. Expanded Polypropylene exhibited variability in density with sample size, and observable variability in the material macrostructure; however, the dependence of the measured mechanical properties on sample size was modest. Low Density Polyethylene was found to have a relatively consistent cell size at the macrostructure level, and the material density did not vary significantly with sample size. In a similar manner, the dependence of measured mechanical properties on sample size was modest. The effect of sample size was identified to be material specific, and it is recommended that this be assessed using sample-specific density measurements and considering different sized samples when testing foam materials.

1. Introduction and background

Polymeric foam materials are widely used as energy absorbing or energy management materials for enhanced protection of the human body in impact scenarios such as vehicle crash, sports protection equipment, and military applications [1]. Important properties of polymeric foams include a low density and high specific energy absorption, where the absorbed energy per unit volume is approximated as the area beneath the stress-strain curve [2]. Using polymeric foams for protection applications, and implementation into Computer Aided Engineering (CAE) requires a good understanding of foam mechanical properties, the dependency on deformation rate, and variability of the material properties. In general, the mechanical properties of foams can be modified by changing the foam density for a given material [2]. Deformation rates in impact events for packaging, sports equipment and protective headwear may range from 10^0 s^{-1} to 10^2 s^{-1} while deformation rates in military applications can exceed 10^3 s^{-1} [1], with the typical mode of loading being compression of the foam.

The mechanical response of closed-cell foam can be characterized by three phases of deformation [2]. Under small deformations (strains less than approximately 5%), a linear elastic response occurs where the cell walls bend or distort to accommodate deformation. The second phase of deformation is the plateau region,

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where large plastic or elastic deformations occur at modestly increasing stress levels, primarily related to cell wall buckling, and corresponding to a large portion of the material energy absorption in impact scenarios. The third stage of deformation is known as densification, occurring as the foam cells are compacted leading to a dramatic increase in material stiffness and stress levels. It is important to note that densification does not initiate when all the voids in the foam are eliminated. Cell edges and walls can interact prior to reaching the theoretical value of zero void volume. The onset of densification can occur at compressive engineering strains as low as 60%, where the stress in the material begins to increase dramatically until the zero void ratio is approached. Many of the important characteristics of foam material behaviour can be related to the foam material density. Gibson and Ashby [2] provide several relationships to describe the plateau stress and densification as a function of material density. In general, the material elastic modulus and plateau stress increase with increasing density while the strain to densification decreases with increasing density [3].

Most polymeric foams exhibit sensitivity to strain rate [1,4–6], which may be observed as creep or relaxation response at low deformation rates and as an increase in the modulus, an increase in the plateau stress level, and a decrease of the densification strain under increasing deformation rate compressive loading. The sensitivity of a material to deformation rate may also depend on the material density [2,7]. The rate dependency of polymeric foams is attributed to the viscoelastic properties of the base material, cell collapse or rupture, locking mechanisms that may occur between adjacent deforming cells, movement of gas (air) within the foam, and frictional forces. The change in densification strain is attributed to deformed cell orientations and their inability to re-orient at high deformation rates to minimize the volume of the compressed material.

Polymeric foam materials may also exhibit local variability in density, owing to the method of manufacture and resulting material structure, and therefore potentially exhibit variability in mechanical response. Polymeric foams exhibit a wide variety of macrostructures including open cells, partially open cells, and closed cells. Three common polymeric foams include Low-Density Polyethylene (LDPE), Expanded Polystyrene (EPS) and Expanded Polypropylene (EPP). Low-Density Polyethylene foam can be manufactured as a closed-cell elastomeric foam using an extrusion or cross-linking process, often with a resulting local variability in density. Expanded polystyrene is a closed-cell elasto-plastic foam made from beads of material, which are expanded by entrapped pentane gas and are then moulded into solid form using steam and pressure. Expanded Polypropylene is also an elastomeric closed-cell bead foam, with some level of plasticity, that is moulded using heat and pressure. Since the pre-process beads vary in size for EPS and EPP, so does the final cell structure of the foam.

Measuring the mechanical response of polymeric foams at low or quasi-static deformation rates (~0.01 s^{-1}) is relatively straightforward [1], allowing for a variety of sample dimensions and uniform loading of the foam. At quasi-static deformation rates, the maximum sample size is often determined by the load cell capacity and desired maximum strain. High resolution is required to measure response in the elastic and plateau regions, while high load capacity is required when the foam reaches densification. Intermediate deformation rates, on the order of 100 s^{-1}, are achieved through high inertia devices and impact loading of test materials, such as a drop tower or pendulum impact test apparatus. At intermediate loading rates, the sample size is limited by the requirement to overwhelm the sample and achieve uniform deformation. In the current study, the range of sample sizes was selected based on the quasi-static and intermediate deformation test requirements. High deformation rate loading of low impedance materials, such as polymeric foams, can present challenges with respect to sample size and the achievement of uniform deformation during the test, owing to the characteristically low wave speed and correspondingly low impedance of these materials [8]. The most widely used method for measuring material properties at high deformation rates is the Split Hopkinson Pressure Bar (SHPB) or Kolsky bar apparatus [9]. Originally proposed by Kolsky [10], the method was developed for high deformation rate testing of metallic materials. This method has more recently been adapted for low impedance materials using two principal methods: incorporation of pulse shaping to increase the rise time of the incident wave to achieve equilibrium [11,12] and the use of low impedance bars to decrease rise time and improve the signal to noise ratio of the output [13–15]. However, one challenge with many methods is that relatively small samples are required for testing, on the order of 6–12 mm in diameter and 3–6 mm in length, are required. A non-uniform compaction wave may be observed in larger samples [16] and anisotropy may be present [17] depending on the material type and manufacturing methods.

Given that foam materials are cellular in nature, and the size of the cells as well as potential voids in the material may vary, a dependency on sample size may occur, along with corresponding variation in mechanical properties of the foam. The aim of this study was to measure the mechanical properties of three polymeric foam materials, at two different densities, for low to intermediate deformation rates, and evaluate the effect of sample size on the mechanical response and deformation rate sensitivity.

2. Methods

Compressive mechanical testing was undertaken on two different densities of Low-Density Polyethylene (LD45, LD70), Expanded Polystyrene (EPS35, EPS44) and Expanded Polypropylene (EPP35, EPP44) (Table 1). The materials were received in sheet form, with varying thickness from 20 to 25 mm. The as-received sheet dimensions were measured, taking care not to deform the material and the material was weighed to calculate the sheet material density (Table 2) using an average of 8 thickness measurements. It was found that the material thickness was relatively consistent within the material sheets, but did vary between the material sheets. The highest variability in thickness was 0.113 mm (standard deviation, LD70), while the largest variability in sheet density was 1.52 kg/m^3 (standard deviation, EPP44) for Expanded Polypropylene. It should be noted that the sheet densities did not quantify density variations, if any, within the material sheet. This aspect was addressed by calculating density for individual samples.

The structure of three foam materials with similar nominal densities of 70 kg/m^3 (LD70, EPP44 and EPS44) was investigated using a Scanning Electron Microscope for qualitative evaluation of the macrostructure.

2.1. Sample preparation

Samples were removed from the material sheets away from the edges to avoid edge effects (Fig. 1), with 3 repeats and 3 sample sizes used in the quasi-static study (9 samples per material), and 5 repeats for 3 samples sized used in intermediate rate tests (15 samples per material) (Table 1). Several methods of sample manufacture were investigated. The final method that provided consistent results was to use a hole saw without an arbour to core out samples of the desired diameter. Three nominal sample diameters were considered in the study: 10 mm (small), 17 mm (medium) and 35 mm (large) (Fig. 2), with the axis of the cylinder oriented in the through-thickness direction. In some cases, the